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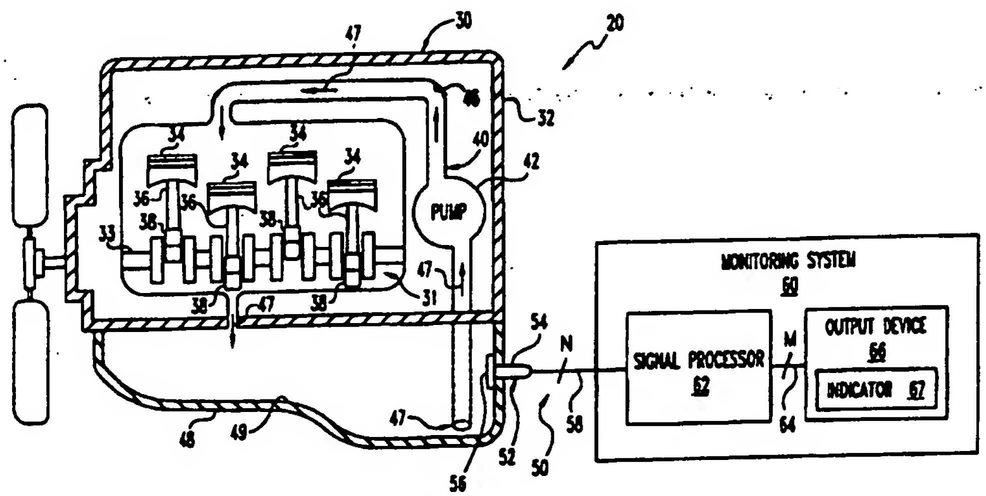

(57) Abstract

An acoustic sensor (52) is disclosed to detect quality of oil or a lubricating liquid resident in a machine (30). The acoustic sensor (52) may include a piezoelectric element (56) configured as a resonator to indicate a change in the property of an oil or lubricating liquid as a function of resonant frequency. Such a sensor (52) may be positioned in an engine (32) having a lubrication system (40) and coupled to a signal processor (62) to provide an indication of when the lubricant has degraded to an extent requiring replacement. Processor (62) may be part of a monitoring system (60) including an output device (66) to provide the indication. In further aspect, sensor (52) is employed to detect viscosity of oil or another liquid residing in a machine in situ.

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IN SITU OIL QUALITY EVALUATION WITH AN ACOUSTIC SENSOR

REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application No. 60/020,898 filed on June 27, 1996.

BACKGROUND OF THE INVENTION

The present invention relates to the evaluation of a liquid with a sensor, and more particularly, but not exclusively relates to a system to detect quality of an oil or lubricating liquid as it resides in a mechanical device.

Monitoring the quality of lubricating, transmission or hydraulic liquids is very important in transportation vehicles and in a variety of industrial equipment such as engines, pumps, and cranes. In the case of transportation vehicles, monitoring the oil quality in the engine and transmission is perhaps the single most important element of preventive maintenance. Generally, there are no commercially available on-board sensors which will monitor oil quality and prompt replacement on an "as needed" basis. As a result, the oil is typically changed after a preset operating interval. Depending on driving conditions, this interval may be too short or too long. An interval which is too short amounts to wasting good motor oil, and an interval which is too long results in excess wear on the automobile engine, and a shorter overall lifetime for the vehicle.

The ability to monitor the quality of a liquid as it resides in a vehicle or other mechanical equipment is needed to improve performance and extend equipment life-time.

Also, this technique would improve recycling and disposal rates of a variety of industrial oils, which in turn would have a positive impact on many environmental conditions such as air and soil pollution, and also would lead to significant energy savings. The cost of operating vehicles and machinery requiring lubricating oils would most likely be reduced.

In recent years, several attempts have been made to provide a viable and commercially practical in situ sensor for determining oil quality. Sensors based on electrochemical, fiber optic, electric impedance, and voltametric principles of operation have been proposed for monitoring engine oil quality. However, to date, their performance has been generally unsatisfactory. Typically, these sensors show poor correlation between measured quality and oil degradation, and exhibit bad reproducibility, fast aging, or large drift. U.S. Patent Nos. 5,523,692 to Kuroyanagi et al., 5,435,170 to Voelker et al., 5,274,335, to Wang et al., 5,200,027 to Lee et al., 5,089,780 to Megerly, 4,741,204 to Luck et al., 4,675,662 to Kondo et al., 4,646,070 to Yasuhara et al., and 3,876,935 to Guillermie et al. are cited as representative examples of these types of sensors.

Therefore, a need still exists for a reliable and cost effective sensor to monitor quality of oils and lubricating liquids in situ. The present invention satisfies this need and provides other significant advantages.

SUMMARY OF THE INVENTION

The present invention relates to evaluation of liquids with a sensor. Various aspects of the invention are novel, non-obvious, and provide various advantages. While the actual nature of the invention covered herein can only be determined with reference to the claims appended hereto, certain features which are characteristic of the preferred embodiment disclosed herein are described briefly as follows.

One feature of the present invention is a sensor for evaluating a liquid. In one aspect of this feature, the sensor is of the acoustic type and is useful to determine quality of an oil or lubricating liquid. In another aspect, a sensor is utilized to detect viscosity of a liquid in order to determine whether the liquid has become degraded. In still another aspect, a machine containing oil and one or more sensors are included in a system for evaluating the quality of the oil as it resides in the machine. To facilitate this in situ evaluation, the system may also include a signal processor responsive to signals from the one or more sensors and an output device responsive to an output signal from the processor.

In another feature of the present invention, a machine is provided with several moveable parts. The machine has a lubrication system configured to provide a liquid to lubricate the parts. The lubrication system includes an acoustic sensor having at least a portion positioned to be mechanically loaded by the liquid while in the lubrication system. The sensor is configured to vibrate while being loaded by the liquid to provide a sensor signal. A monitoring system is operatively coupled to the sensor to receive the sensor signal. The monitoring system indicates degradation of the liquid as a function of this sensor signal.

In a further feature of the present invention, an

internal combustion engine is provided that defines a space configured to contain a lubricating liquid. A sensor having a piezoelectric element is coupled to the engine. The sensor contacts the liquid in the space during operation of the engine to generate a sensor signal corresponding to quality of the liquid. A signal processing circuit is operatively coupled to the sensor to receive the sensor signal. This circuit generates an output signal as a function of the sensor signal which is representative of quality of the liquid.

In another feature, a machine has several movable parts that are configured to provide motive power. This machine defines a passageway configured to circulate oil through at least a portion of the machine. A sensor is coupled to the machine to contact the oil in the machine during operation. The sensor generates a sensor signal corresponding to viscosity of the oil in situ. An output device responsive to the sensor signal provides an indication corresponding to quality of the oil, the indication being determined as a function of the viscosity of the oil.

In yet another feature, at least a portion of a sensor is positioned to contact oil inside a machine. The machine defines a path for the circulation of the oil therein. Also, the machine includes several moving parts in contact with the oil during operation. The viscosity of the oil is sensed in the machine with the sensor while the machine is operating. Degradation of the oil is determined from the viscosity with a monitoring system operatively coupled to the machine. The sensor may include a piezoelectric element.

In still a further feature, oil is circulated through a machine with several moving parts, the parts being in contact with the oil during said circulation. An acoustic sensor is mechanically loaded with the oil during this circulation. The sensor is carried with the machine. A property of the oil is sensed by causing the sensor to

resonate during loading. Degradation of the oil is determined from the property of the oil with a monitoring system operatively coupled to the sensor.

A further feature of the present invention is an oil quality sensor capable of discerning between new unused oil and old used oil. This sensor may also be used to detect degradation due to contamination from various compounds to which oil is commonly exposed, such as water, glycol, and gasoline.

Accordingly, it is one object of the present invention to determine quality of a liquid using an acoustic sensor.

Another object of the present invention is to provide a system configured to determine quality of a liquid as it resides in mechanical equipment.

Still another object is to detect degradation of oil or another liquid residing in a machine and provide an indication to an operator to prompt replacement of the oil or other liquid when a predetermined degree of degradation is detected.

A further object of the present invention is to detect the viscosity of oil with a sensor to determine when the oil needs to be replaced.

An additional object of the present invention is to detect the viscosity of a liquid residing in a machine with a sensor in order to determine quality of the liquid.

Yet another object of the present invention is to detect degradation of oil with an acoustic sensor and prompt replacement when degradation becomes too severe. Such degradation may result from the build-up of sludge and other contaminants such as water, glycol, and gasoline.

Further objects, features, benefits, aspects, and advantages of the present invention will become apparent from the drawings and description provided herein.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic view of a mechanical system of one embodiment of the present invention.

Fig. 2 is a schematic view of a vehicle system embodiment of the present invention that incorporates the system of Fig 1.

Fig. 3 is a partial schematic view showing a first embodiment of the oil quality evaluation system of Fig. 1 in greater detail.

Fig. 3a is a partial schematic view showing a second embodiment of the oil quality evaluation system of the present invention.

Figs. 4a and 4b are graphs illustrating the resonant behavior of the sensors of Figs. 3 and 3a. Fig. 4a illustrates the change in amplitude with frequency and Fig. 4b illustrates the change in phase with frequency.

Figs. 5a and 5b are graphs illustrating certain operational aspects of the evaluation system of Fig. 3. Fig. 5a graphically depicts a D.C. voltage output at a selected point versus frequency. Fig. 5b is a bar graph illustrating a region of the graph of Fig. 5a in greater detail.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

For the purposes of promoting an understanding of the principles of the invention, reference will now be made to the embodiments illustrated in the drawings and specific language will be used to describe the same. It will nevertheless be understood that no limitation of the scope of the invention is thereby intended. Any alterations and further modifications in the described processes, systems, and devices, and any further applications of the principles of the invention as described herein are contemplated as would normally occur to one skilled in the art to which the invention relates.

Generally, modern engine oils are very complex substances. Typically, today's engine oils include not only the base crude or synthetic oil, but also numerous additives such as antioxidants, detergents, and oil thickeners. Therefore, the mechanisms of oil breakdown are often just as complex. Combustion products from the engine's cylinders eventually overwhelms these additives, causing a build-up of byproducts and oxidation. In addition, the oil can be contaminated by various substances from throughout the engine such as wear metal, water, gasoline, ethylene, glycol, and dust. It has been found that many of the aforementioned degradation processes affect the viscosity of the oil. This discovery is described in detail in U.S. Provisional Patent Application Serial Number 60/020,898 filed on June 27, 1996 which is hereby incorporated by reference in its entirety.

Therefore, in accordance with one aspect of the present invention, oil quality is monitored in situ by determining viscosity of the oil with an appropriate sensor. In another aspect, oil quality information is combined with other parameters such as oil temperature, type, and grade. In a further aspect, viscosity of a liquid as it resides in a

machine is provided with a sensor. In still another aspect, an acoustic sensor is used to evaluate one or more properties of the liquid in situ.

Fig. 1 schematically depicts mechanical system 20 of the present invention. System 20 includes a machine 30 with several moving parts 31 in the form of internal combustion engine 32. Engine 32 includes crankshaft 33 configured to provide motive power. Crankshaft 33 is driven by several pistons 34 each moveably connected to crankshaft 33 by a corresponding connecting rod 36 and bearing 38. Pistons 34 are each configured to reciprocate in a combustion chamber (not shown) during operation of engine 32 to turn crankshaft 33 in a conventional manner. Preferably, engine 32 is configured for conventional four-stroke, Spark Ignited (SI) operation.

Engine 32 includes lubrication system 40. Lubrication system 40 is configured to provide a lubricating liquid, such as oil, to moving parts 31. Lubrication system 40 includes a pump 42 configured to circulate oil through passageway 46 defined by machine 30. Passageway 46 is in fluid communication with oil pan 48. Oil pan 48 defines space 49 to collect oil from moving parts 31. Oil is circulated through passageway 46 and oil pan 48 in the direction indicated by arrows 47.

Mechanical system 20 also includes in situ oil evaluation system 50. Evaluation system 50 has acoustic sensor 52. Acoustic sensor 52 includes a mounting member 54 and a piezoelectric element 56. Mounting member 54 affixes acoustic sensor 52 to machine 30 to be carried therewith. When so affixed, acoustic sensor 52 is configured to position at least a portion of piezoelectric element 56 inside oil pan 48 to contact oil contained therein. Preferably, mounting member 54 is configured to provide for the long-term placement of piezoelectric element in contact

with oil as it circulates along the path defined by arrows 47.

Signal paths 58, numbering "N" in quantity, operatively couple acoustic sensor 52 to monitoring system 60, where "N" is a positive integer. Evaluation system 50 also includes monitoring system 60. Monitoring system 60 includes signal processor 62. Signal paths 64, numbering "M" in quantity, operatively couple signal processor 62 to output device 66, where "M" is a positive integer. Output device 66 includes an indicator 67. Preferably, indicator 67 is responsive to an output signal from signal processor 62 to provide information in a form which may be perceived by a human operator.

Referring additionally to Fig. 2, vehicle system 70 is illustrated. Vehicle system 70 depicts the implementation of mechanical system 20 into vehicle 72 with like reference numerals identifying like features. Vehicle 72 includes wheels 74 and passenger compartment 76. Preferably, vehicle 72 is arranged for operation as an automobile.

Engine 32 provides the motive power for vehicle 72. Preferably, vehicle 72 includes a conventional drive train with a transmission (not shown) to direct mechanical power provided by engine 32. Vehicle 72 may further include other devices and systems common to conventional automobiles.

Monitoring system 60 is shown mounted within vehicle 72 and is coupled to engine 32 via signal paths 58 and acoustic sensor 52. Acoustic sensor 52 is shown attached to oil pan 48. Monitoring system 60 may be a separate system, or integrated with other systems of vehicle 72. In one embodiment, signal processor 62 includes electronic circuitry that is operable to monitor and integrally control many functions and operational aspects of engine 32 and vehicle 72. For this embodiment, additional operative connections to engine 32 and vehicle 72 are envisioned. In other embodiments, system 60 may be arranged as would occur

to those skilled in the art. Preferably, monitoring system 60 is powered by an electrical system (not shown) of vehicle 72.

Indicator 67 of monitoring system 60 is depicted within passenger compartment 76. Preferably, indicator 67 is positioned to be readily perceived by an operator of vehicle 72. Indicator 67 may be a simple indicator lamp, a gauge, an audible warning device, or such other type of indicator as would occur to one skilled in the art.

Fig. 3 depicts selected aspects of evaluation system 50 in greater detail with like reference numerals identifying like features. Several elements of signal processor 60 are arranged as signal processing circuit 162. Furthermore, additional details of the preferred embodiment of acoustic sensor 52 are illustrated. Piezoelectric element 56 is arranged as piezoelectric resonator (PER) 152 in space 49 of oil pan 48. PER 152 includes an AT cut quartz crystal 153 with electrodes 154, 156 connected thereto. Electrode 156 defines a surface 158 configured to contact oil in space 49. PER 152 is configured so that crystal 153 is mechanically loaded by oil in contact with surface 158. Electrodes 154, 156 are coupled to circuit 162 to define signal paths 58. Preferably, signal paths 58 are provided by an electrically conductive cable or wire; however, other techniques as would occur to one skilled in the art are also envisioned. Mounting member 54 is not shown in Fig. 3 in order to preserve clarity.

Circuit 162 includes controller 164 of a conventional variety. Controller 164 may be an electronic circuit comprised of one or more components. Similarly, controller 164 may be comprised of digital circuitry, analog circuitry, or both. Also, controller 164 may be programmable, an integrated state machine, or a hybrid combination thereof. Preferably controller 164 includes a microprocessor of a known construction suitable for automotive use that has been

conventionally programmed to perform the functions attributed to it.

Voltage Controlled Oscillator (VCO) 166 is operatively coupled to controller 164 by signal path 165. VCO 166 is configured to output a periodic oscillator signal having a frequency dependent on the level of an input voltage. Preferably, the oscillator signal output by VCO 166 is sinusoidal in character. Controller 164 inputs the voltage level controlling the frequency of the VCO 166 oscillator signal along signal path 165. Controller 164 may be configured to deliver an analog voltage directly to VCO 166 or may provide digital data corresponding to the frequency setting voltage that is subsequently converted by a conventional digital to analog converter (not shown) along signal path 165.

The oscillator signal of VCO 166 is provided to PER 152 by one of N signal paths 58 coupled to electrode 154. The oscillator signal selectively stimulates oscillation of crystal 153. VCO 166 is also coupled to signal mixer 172 to provide the oscillator signal.

Signal mixer 172 is also operatively coupled to electrode 156 of PER 152 to receive a sensor signal therefrom. Signal mixer 172 combines the oscillator signal and sensor signal to output a combined signal along signal path 173 operatively coupled to Low Pass Filter (LPF) 174. LPF 174 smooths the combined signal to reduce noise and time varying components of the combined signal that correspond to frequencies above a predetermined limit. Preferably, the filtered signal output by LPF 174 along signal path 175 to controller 164 changes very slowly with time relative to the oscillator, sensor, and combined signals. In one preferred embodiment, LPF 174 is configured with a 6 Hz cutoff frequency.

Controller 164 receives the filtered signal as an input signal either directly or via an analog to digital converter

(not shown) as appropriate. Controller 164 is configured to respond to the input signal from LPF 174 to selectively generate an output signal along one or more of signal paths 64 to output device 66. Controller 164 is also coupled to oil temperature probe 182 by signal path 181. Probe 182 provides a temperature signal corresponding to temperature of the oil in the vicinity of PER 152 in a format compatible with controller 164 and may include amplifiers, analog to digital converters, and such other signal conditioners (not shown) as are required to provide compatibility. Controller 164 is also operatively coupled to an operator input device 184 by signal path 185 which may be used to control various operations of controller 164.

The piezoelectric properties of crystal 153 cause it deform in correspondence with an electrical voltage across electrodes 154, 156. Crystal 153 is configured to provide "shear deformation" along the directions indicated by the double-headed arrow 157. By providing a periodic voltage across electrodes 154, 156 of an appropriate frequency and amplitude, crystal 153 mechanically oscillates, or vibrates, by expanding and contracting along arrow 157. The vibration of crystal 153 in this manner generates acoustic waves in the oil contacted by surface 158.

Piezoelectric resonators (PERs) are generally configured to oscillate with maximum efficiency only at discrete frequencies determined by the size, geometry, and material properties of the piezoelectric material. It has also been discovered that liquid in contact with the boundary of a PER may alter resonance behavior of the PER as described in U.S. Provisional Patent Application 60/020,898 filed June 27, 1996.

It can be shown that changes in the resonant frequency of a PER are due to various mechanical interactions or loading effects between the surface of the crystal and the liquid being sensed. In general, these changes are affected

by many properties of the liquid including: specific density, conductivity, and viscosity. The geometry of the piezoelectric resonator may be selected to enhance sensitivity of the associated resonant frequency to one or more of these properties. For example, in one preferred embodiment of the present invention, changes in the viscosity of an oil that is mechanically loading PER 152 are monitored as a function of the resonant behavior of PER 152 relative to the oscillation signal from VCO 166. For this embodiment, changes in oil viscosity are, in turn, analyzed by controller 164 to determine if the oil has unacceptably degraded.

Crystal 153 of sensor 52 is configured to primarily generate a shear type of wave to sensitivity detect changes in viscosity of oil by perturbations in resonant frequency. Preferably, the resonant frequency of PER 152 is in a range of about 1 to 10 MegaHertz (MHz). More preferably, this range is about 4 to 6 MHz. The components of signal processing circuit 162 are adjusted in accordance with the frequency range of PER 152.

The graphs 500 and 550 depicted in Figs. 4a and 4b, respectively, illustrate the sensitivity of PER 152 to various frequencies. Graphs 500 and 550 were obtained with a test arrangement configured from laboratory equipment functionally comparable to the arrangement of circuit 263 described in connection with Fig. 3a hereinafter. These graphs may also be obtained by sweeping the frequency of VCO 166 and measuring the amplitude and phase change output by PER 156 from electrode 156 versus the stimulus oscillator signal from VCO 166. Referring to Fig. 4a, graph 500 depicts the resonant behavior of PER 152 for several different oil samples in terms of amplitude versus frequency. Vertical scale 502 represents amplitude output by PER 152 in deciBels (dB) with each mark of scale 502 representing a 2 dB change relative to the stimulating

oscillator signal. For vertical scale 502, the amplitude ranges from -25 dB for mark 503 to -45 dB for mark 504. Horizontal scale 506 represents frequency in Hertz (Hz), with each mark of scale 506 representing a 1,875 Hz change of the stimulating oscillator signal. For Horizontal scale 506, the frequency ranges from 4,970,500 Hz for mark 507 to 5,019,250 Hz for mark 508.

Curve 510, represented in a phantom line pattern, corresponds to the response of PER 152 for a degraded sample of oil. Curve 512, represented by a solid line pattern, corresponds to the response of PER 152 for a sample of new 10W30 motor oil. Curve 514, represented by a dashed line pattern corresponds to the response of PER 152 for a sample of new 20W50 motor oil. Notably, at the maxima 516 corresponding to a resonant peak, significant separation of curves 510, 512, 514 may be observed. Similarly, at the minima 520 corresponding to an antiresonant point, separation of curves 510, 512, 514 is significant.

Fig. 4b depicts graph 550 to provide phase versus frequency information about PER 152 for the same samples depicted in Fig. 4a. Vertical scale 552 represents relative phase change in degrees with each mark of scale 552 representing a 10 degree change of phase relative to the stimulating oscillator signal. For vertical scale 552, this relative phase shift ranges from -40 degrees for mark 554 to +60 degrees for mark 503. Horizontal scale 556 represents frequency in Hertz (Hz), with each mark of scale 556 representing a 1,875 Hz change of the stimulating oscillator signal. For horizontal scale 556, the frequency ranges from 4,970,500 Hz for mark 557 to 5,019,250 Hz for mark 558.

Curve 560, represented in a phantom line pattern, corresponds to the response of PER 152 for the degraded sample of oil. Curve 562, represented by a solid line pattern, corresponds to the response of PER 152 for the sample of new 10W30 motor oil. Curve 564, represented by a

dashed line pattern corresponds to the response of PER 152 for the sample of new 20W50 motor oil. Notably, at the minima 570, separation of curves 510, 512, 514 is significant.

Referring generally to Figs. 1-3, 4a, and 4b; the operation of evaluation system 50 is next described. With reference to graphs 500 and 520, a frequency is selected that appears to provide significant separation of oils of different viscosities. In this case, a frequency of 4,997,000 Hz is selected as an initial operating frequency (OF). Controller 164 may be conventionally programmed to ascertain this frequency for generation by VCO 166, and provide different operating frequencies depending on oil type and temperature. In one embodiment, controller 164 may be programmed to determined operating frequencies for various oil types and temperatures through a calibration procedure conducted with the aid of an operator utilizing input device 184.

Controller 164 generates a control signal along signal path 165 to adjust VCO 166 to output a sinusoidal oscillator signal with an Operating Frequency (OF) equal to about 4,997,000 Hz. The oscillator signal (OS) output by VCO 166 to PER 152 and mixer 172 is represented by equation: OS = A_0cosine(OF), where A_0 is the amplitude of the oscillator signal and OF is the operational frequency. The oscillator signal causes crystal 153 of PER 152 to resonate and output a sensor signal that may have a different amplitude and phase compared to the stimulus. The sensor signal (SS) may be represented by the equation: SS = $A_s$cosine(OF + PS), where A_s is the amplitude and PS is the phase shift relative to operating frequency OF.

Mixer 172 receives sensor signal SS and oscillator signal OS and multiplies the respective time varying amplitudes, A_o and A_s, together. It has been found that combining OS and SS tends to enhance sensitivity to

viscosity of the liquid. To further enhance sensitivity to viscosity, mixer 172 also multiplies the two signals by the cosine of the phase shift, cosine(PS). The Combined Signal (CS) output by mixer 172 is expressed as follows:

$CS=A_O*A_S*cosine(PS)$.

Low Pass Filter (LPF) 174 receives the combined signal (CS) along signal path 173 and removes most time varying components to provide a generally steady D.C. output that typically changes with variation in viscosity of the oil in oil pan 48. Referring additionally to Figs. 5a and 5b, an experimentally obtained voltage corresponding to the Filtered Output Signal (FOS) of LPF 174 on signal path 175 is illustrated.

Fig. 5a depicts graph 600 of D.C. voltage versus frequency for a signal corresponding to FOS provided by LPF 174. Horizontal scale 602 represents voltage in 0.005 volt increments. For scale 602, the voltage at mark 603 is +0.005 volts and the descends to -0.025 volts at mark 604. Vertical scale 606 represents frequency in 1,500 Hz increments from 4,970,000 Hz at mark 607 to 5,009,000 Hz at mark 608. Curve 610 in the phantom line pattern corresponds to the degraded oil sample described in connection with Figs. 4a and 4b. Curve 612 in the solid line pattern corresponds to the new 10W30 motor oil sample, and curve 614 in the dashed line pattern corresponds to the new 20W50 motor oil sample. The minima at 618 corresponds to the operating frequency of 4,997,000 Hz where separation of curves 610, 612, 614 representing oils of diverse age, degradation, and viscosity is greatest.

Fig. 5b provides a bar chart 620 further illustrating the separation between curves 610, 612, 614 at minima 618 of graph 600. The horizontal scale 622 corresponds to voltage in millivolts (mv) in absolute-valued 5 mv increments, descending from 25 mv for mark 623 to 0 mv for mark 624. Bar 630 corresponds to about a 24 mv level for curve 610.

Bar 632 corresponds to about a 20 mv level for curve 612, and bar 634 corresponds to about a 17 mv level for curve 614.

Controller 164 is configured to analyze FOS from LPF 174 using conventional techniques to determine whether a shift in viscosity of oil in space 49 is of a type indicative of degraded oil. Controller 164 may be programmed in a conventional fashion with one or more routines to periodically acquire data from LPF 174 and analyze this data. Typically, this analysis includes comparing a current data input from LPF 174 to one or more past inputs to determine if a change has occurred.

Controller 164 may utilize the temperature signal from probe 182 to further distinguish viscosity changes due to oil temperature from viscosity changes due to degradation. For example, when a multigrade oil is used, such as 10W40, the ideal viscosity is between 1300 and 2600 centistokes (cs) at about -17.8 degrees Celsius and between 12.9 and 16.8 cs at about +98.9 degrees Celsius. This known variation of oil viscosity with temperature may be accounted for by programming controller 164 with a corresponding data look up table. The temperature signal from probe 182 may then be used to enter the table to assist in determining if a given viscosity change detected with PER 152 is due to a shift in temperature of the oil, as detected by probe 182, or a change in quality of the oil. This table may include data for a number of oil types selectable by operator input device 184.

In one embodiment, operator input device 184 includes a switch or similar data entry device to input a signal indicating oil has been changed. In response, controller 164 initiates a calibration mode including the performance of a number of periodic readings of the input signal from LPF 174 during the initial operation of engine 32 with the new oil. This mode may be continued for a predetermined

range of oil temperatures as determined from the temperature signal provided by probe 182 to load a look table in controller 164 with corresponding "baseline" oil viscosity data. Once this calibration is complete, the controller returns to a monitoring mode to determine whether oil degradation has occurred relative to this baseline data. In still other embodiments, an abrupt decrease in viscosity at engine start-up without a corresponding temperature change may cause controller 164 to switch to a calibration mode automatically.

The analysis performed by controller 164 may include statistical treatment of the data that enhances the reliable prediction of oil degradation. Analysis may include scanning the FOS for each of a number of different Operating Frequencies (OF) of the oscillator signal (OS) provided by VCO 166 under the direction of controller 164. Controller 164 may compare past and present FOS valves for each frequency in determining whether a viscosity shift indicative of oil degradation has occurred. Once analysis indicates the oil has degraded beyond a minimum acceptable threshold, then controller 164 is configured to generate an output signal along signal path 64 to output device 66. This output signal is configured to provide an indication via indicator 67 to an operator to prompt the operator to change the oil within a predetermined time period or other usage measurement of machine 30. For the vehicle system 70 embodiment, the indication may, for instance, be configured to warn the operator to change the oil within a predetermined mileage. Alternatively, the output signal may continuously be updated to indicate on-line quality of the oil through a gauge arrangement of indicator 67. In still other embodiments, a combination of these techniques or such other techniques as would occur to one skilled in the art may be employed.

Figs. 5a and 5b were generated utilizing one

experimental embodiment of the present invention resembling circuit 162. In this embodiment, an appropriately programmed personal computer served as controller 164 which was operatively coupled to a Hewlett Packard model 4195A network/spectrum analyzer configured to serve as VCO 166. The model 4195A network/spectrum analyzer was coupled to electrode 154 of PER 152. PER 152 was positioned in a test cell configured for successive exposure to oil samples. Electrode 156 of PER 152 was coupled to one input of an Anzac model MP-140 mixer to provide the signal processing operations described in connection with mixer 172. The model 4195A Analyzer was coupled to another input of the model MP-140 mixer. A low pass filter with a 6 Hz cutoff frequency was coupled to an output of mixer MP-140 to serve as LPF 174. The voltage output from the low pass filter was coupled to an analog to digital converter provided by a data acquisition card embedded in the personal computer to acquire the input signal from the low pass filter. With this arrangement, the frequency of the oscillator signal used to stimulate PER 152 was swept over the range indicated in Fig. 5a for each sample, and corresponding data accumulated in the personal computer. The personal computer was programmed to combine the data acquired for the degraded engine oil, new 10W30 engine oil, and new 20W50 engine oil samples to provide the combined curves of graph 600 relative to the model 4195A analyzer periodic signal input.

Fig. 3a schematically illustrates oil quality evaluation system 250 configured as a replacement for evaluation system 50 of the embodiments of Figs. 1-3 with like reference numerals indicating like features. In evaluation system 250, signal processor 262 replaces signal processor 62. Signal processor 262 includes processing circuit 263 with digital processor 264. Digital processor 264 is operatively coupled to Digitally Controlled Oscillator (DCO) 266 by signal pathway 265. Digital processor 264 is configured to

provide digital control signals to DCO 266. DCO 266 responds to certain digital commands from digital processor 264 to adjust the frequency of a periodic electrical signal output on signal path 267. Path 267 is electrically coupled to electrode 154 to selectively stimulate oscillation of PER 152.

The response of PER 152 to the oscillator signal along path 267 is detected by signal detector 272 electrically coupled to electrode 156 of sensor 252 by signal path 270. Detector 272 formats the sensor signal received along signal path 270 into a digital format which is then output as a response signal along signal path 273 operatively coupled to digital processor 264. Digital processor 264 is also operatively coupled to input device 268 including temperature probe 269. Temperature probe 269 is configured to detect temperature of the oil loading PER 152. Input device 268 may also include an operator input apparatus such as a switch to generate an operator input signal indicating that the oil has been changed, the type of oil, or other data pertinent to the determination of oil quality with system 250.

Digital processor 264 is configured, preferably through conventional software or firmware programming, to sweep the frequency of DCO 266 over a selected range to observe resonant behavior of sensor 152 as depicted, for instance, in Figs. 4a and 4b. This frequency sweep is performed on a periodic basis and digital processor 264 is further configured to determine frequencies corresponding to resonance of PER 152 for each sweep.

Processor 264 executes one or more routines to analyze the resonant frequency data from each sweep. This programmed analysis includes comparing the data from the current sweep data to data from one or more earlier frequency sweeps to determine whether the shift indicates the type of viscosity change in the oil indicative of oil

degradation. Preferably, the program accounts for viscosity changes resulting from temperature shifts as monitored by probe 269 and other outside factors influencing viscosity besides oil degradation. Calibration and data tables to account for expected changes in oil viscosity as described in connection with controller 164 may be incorporated into the routines executed by processor 264. Averaging of the sweep data and various other statistical treatments may be included in the programming to enhance the determination of whether a given viscosity change is of the type indicating a permanent degradation of the oil. Once digital processor 264 determines the oil quality has changed, processor 264 compares the level of degradation to a minimum standard and generates an output signal corresponding to a warning that the oil should be changed. Output device 66 responds to the output signal to provide an appropriate indication to the operator to prompt changing of the oil.

In other embodiments, it is envisioned that different resonator configurations and signal processing arrangements may be employed as would occur to those skilled in the art. In one alternative embodiment, a piezoelectric torsional resonator (PTR) may be employed in the KiloHertz (KHz) to 1 MHz frequency range. In still other embodiments, an acoustic sensing arrangement is utilized to detect properties indicative of oil or another liquid residing in a machine as would occur to one skilled in the art. In further embodiments, the viscosity of a liquid flowing through a machine may be detected in situ.

Thus, among the advantages of the present invention is to detect properties of an oil and other liquids with an acoustic sensor positioned in situ. The acoustic sensor may includes a piezoelectric material such as quartz, a piezoelectric ceramic material, or such other piezoelectric material as would occur to those skilled in the art. Notably, quartz and common piezoelectric ceramics typically

withstand the harsh environment frequently presented by in situ engine oil. In various embodiments, the liquid being monitored in accordance with the present invention may be in an engine, transmission, hydraulic circuit, or such other machine as would occur to those skilled in the art.

As used herein, it should be appreciated that: "variable," "criterion," "characteristic," "quantity," "amount," "value," "buffer," "constant," "flag," "data," "record," "memory space," "memory location," "threshold," "input," "output," "pixel," "image" (or a region thereof), "matrix," "command," "look-up table," or "memory location" each generally correspond to one or more signals within processing equipment of the present invention.

It is contemplated that various operators, operations, stages, conditionals, procedures, thresholds, routines, programs, and processes described in connection with the present invention could be altered, rearranged, substituted, deleted, duplicated, combined, or added to other processes as would occur to those skilled in the art without departing from the spirit of the present invention.

All publications, patents, and patent applications cited in this specification are herein incorporated by reference as if each individual publication, patent, or patent application were specifically and individually indicated to be incorporated by reference and set forth in its entirety herein.

While the invention has been illustrated and described in detail in the drawings and foregoing description, the same is to be considered as illustrative and not restrictive in character, it being understood that only the preferred embodiment has been shown and described and that all changes and modifications that come within the spirit of the invention are desired to be protected.

CLAIMS

What is claimed is:

1. A combination, comprising:

a machine with several moveable parts, said machine having a lubrication system configured to provide a liquid to lubricate said parts;

said lubrication system including an acoustic sensor, at least a portion of said sensor being positioned to be mechanically loaded by the liquid in said lubrication system, said sensor being configured to vibrate while being loaded by the liquid to provide a sensor signal; and

a monitoring system operatively coupled to said sensor to receive the sensor signal, said monitoring system being configured to indicate degradation of the liquid as a function of the sensor signal.

2. The combination of claim 1, wherein the sensor signal corresponds to viscosity of the liquid.

3. The combination of claim 1, further comprising a vehicle powered by said machine and wherein said machine includes an internal combustion engine and said parts include a number of pistons.

4. The combination of claim 1, wherein said monitoring system includes a signal processor coupled to an output device, said signal processor is configured to generate an output signal as a function of said sensor signal and a reference signal, and said output device responds to said output signal to provide an indication prompting replacement of the liquid.

5. The combination of claim 1, wherein said sensor includes

a piezoelectric quartz crystal resonator that is electrically coupled to said monitoring system and said resonator is configured to provide shear waves when vibrating in response to an oscillating electrical input.

6. A combination, comprising:

an internal combustion engine defining a space configured to contain lubricating liquid.

a sensor coupled to said engine, said sensor having a piezoelectric element, said sensor being configured to contact the liquid in said space during operation of said engine to generate a sensor signal corresponding to quality of the liquid; and

a signal processing circuit operatively coupled to said sensor to receive the sensor signal, said circuit being configured to generate an output signal as a function of the sensor signal, the output signal being representative of quality of the liquid.

7. The combination of claim 6, wherein said signal processing circuit includes:

an electric oscillator coupled to said sensor to provide an oscillator signal to stimulate resonance of said sensor; and

a mixer configured to combine said sensor signal and said oscillator signal.

8. The combination of claim 7, wherein said mixer provides a combined signal as a function of amplitude of the sensor signal, amplitude of the oscillator signal, and phase difference between the sensor signal and oscillator signal.

9. The combination of claim 7, wherein said element is arranged as a piezoelectric resonator.

10. The combination of claim 7, further comprising a low pass filter configured to receive a combined signal from the mixer.

11. The combination of claim 6, wherein said piezoelectric element includes an AT cut quartz crystal.

12. The combination of claim 6, further comprising a vehicle powered by said engine.

13. The combination of claim 6, wherein said sensor signal corresponds to viscosity of a lubricating oil for said engine.

14. A combination, comprising:

a machine having several moveable parts configured to provide motive power, said machine defining a passageway configured to circulate oil through at least a portion of said machine;

a sensor coupled to said machine, said sensor being configured to contact the oil in said machine during operation of said machine, said sensor being further configured to generate a sensor signal corresponding to viscosity of the oil in situ; and

an output device responsive to the sensor signal to provide an indication corresponding to quality of the oil, the indication being determined as a function of the viscosity of the oil.

15. The combination of claim 14, further comprising a vehicle powered by said machine and wherein said machine includes an internal combustion engine and said parts include a number of pistons.

16. The combination of claim 14, wherein the indication is

configured to prompt an operator to change the oil in said machine based on a detected change of the viscosity of the oil.

17. The combination of claim 14, wherein said sensor includes a piezoelectric element and further comprising a signal processing circuit coupled to said output device and said sensor, said circuit being configured to provide an output signal to said output device corresponding to the indication.

18. The combination of claim 17, wherein said circuit includes:

an electric oscillator coupled to said sensor to provide an oscillator signal to stimulate resonance of said piezoelectric element and;

a mixer configured to combine said sensor signal and said oscillator signal.

19. The combination of claim 18, wherein said sensor includes a piezoelectric resonator.

20. A combination, comprising:

contacting lubricating liquid to mechanically load an acoustic sensor with the liquid, said contacting including positioning at least a portion of the acoustic sensor inside a lubrication system of an engine;

sensing a property of the liquid by controllably vibrating the sensor during said contacting; and

determining degradation of the liquid from the property of the liquid with an engine monitoring system operatively coupled to the sensor.

21. The combination of claim 20, further comprising operating the engine during said sensing.

22. The combination of claim 20, wherein the property corresponds to viscosity of the liquid and said determining includes comparing the viscosity provided by said sensing to a predetermined threshold indicative of the degradation of the liquid.

23. The combination of claim 20, wherein the lubricating liquid includes oil.

24. The combination of claim 20, wherein said sensing includes vibrating the sensor at a resonance frequency.

25. The combination of claim 20, further comprising providing an indication of the degradation of the liquid to prompt an operator to replace the liquid.

26. A combination, comprising:

circulating an oil through a machine with several moving parts, the parts being in contact with the oil during said circulating;

mechanically loading an acoustic sensor with the oil during said circulating the acoustic sensor being configured to be carried with the machine;

sensing a property of the oil by causing the sensor to resonate during said loading; and

determining degradation of the oil from the property of the oil with a monitoring system operatively coupled to the sensor.

27. The combination of claim 26, further comprising operating the machine during said circulating and said sensing.

28. The combination of claim 26, wherein the property

corresponds to viscosity of the oil and said determining includes comparing a viscosity level of the oil provided by said sensing to a predetermined threshold indicative of the degradation of the oil.

29. The combination of claim 26, further comprising providing an indication of the degradation of the liquid to prompt an operator to replace the liquid.

30. The combination of claim 26, wherein the machine includes an internal combustion engine and the parts include a number of pistons, and further comprising mounting the engine and the monitoring system in a vehicle.

31. A combination, comprising:

positioning at least a portion of a sensor into contact with oil inside a machine, the machine defining a path for the circulation of the oil therein and including several moving parts in contact with the oil during operation;

sensing viscosity of the oil in the machine with the sensor while the machine is operating; and

determining degradation of the oil from the viscosity with a monitoring system operatively coupled to the machine.

32. The combination of claim 31, wherein the sensor includes a piezoelectric element.

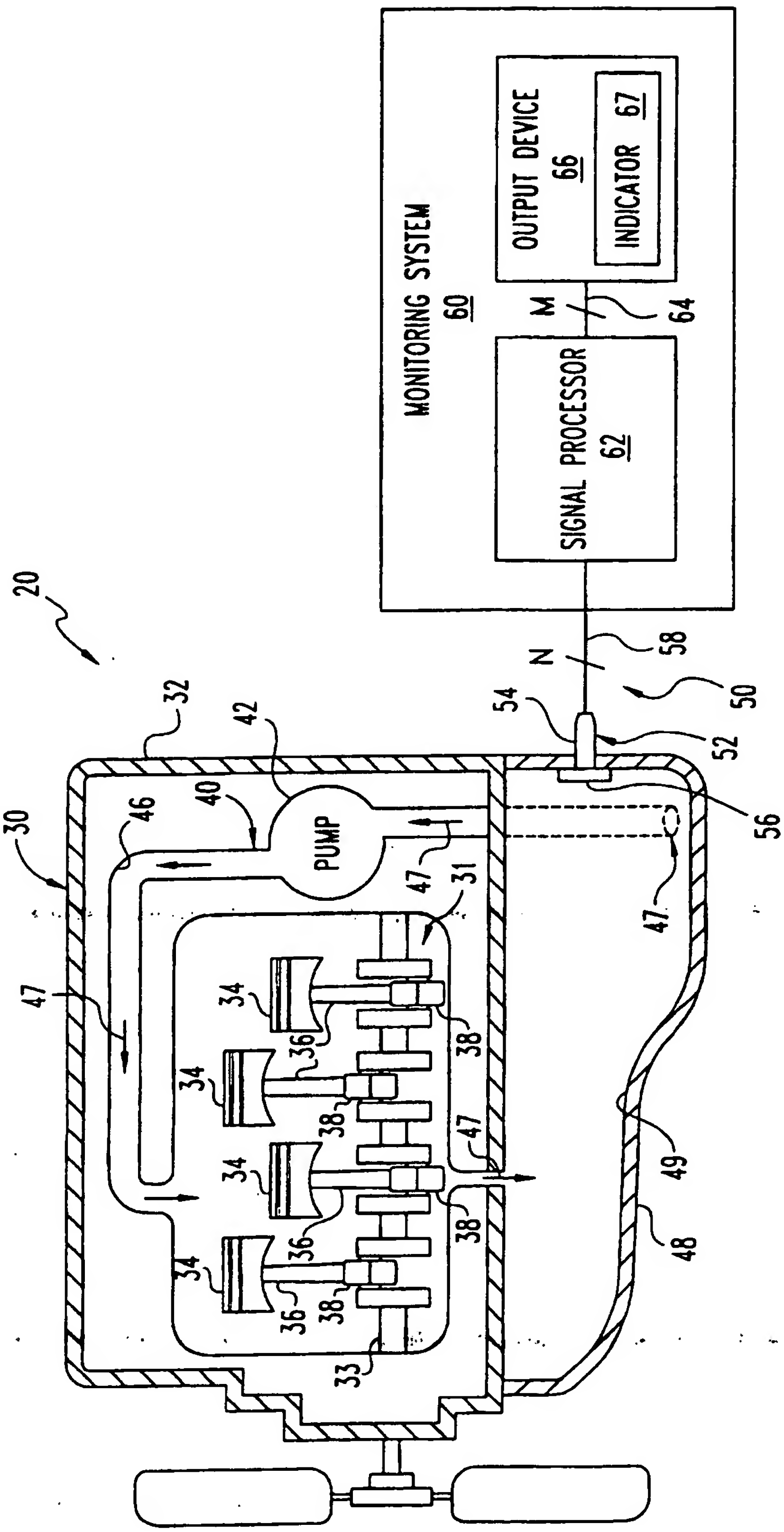
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Fig. 1

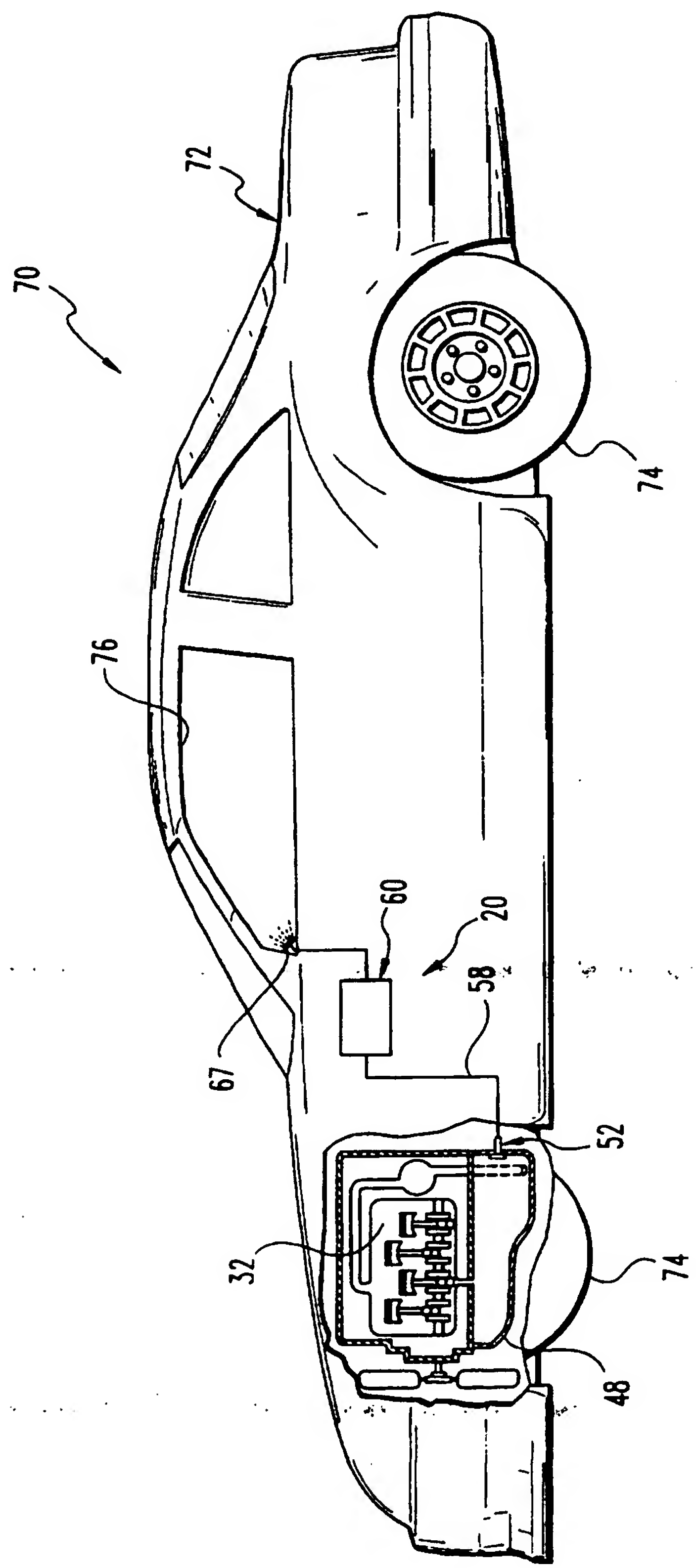
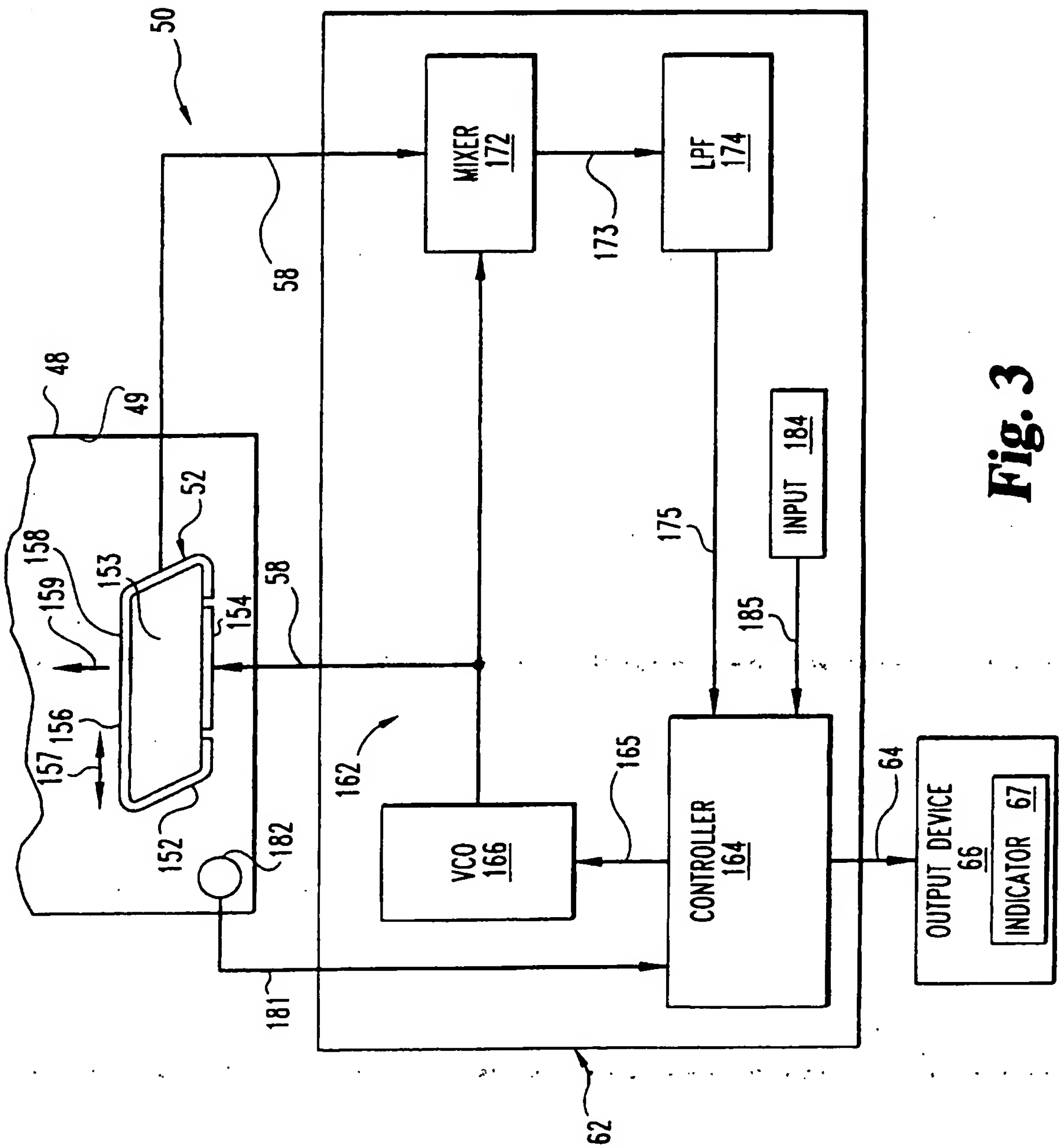


Fig. 2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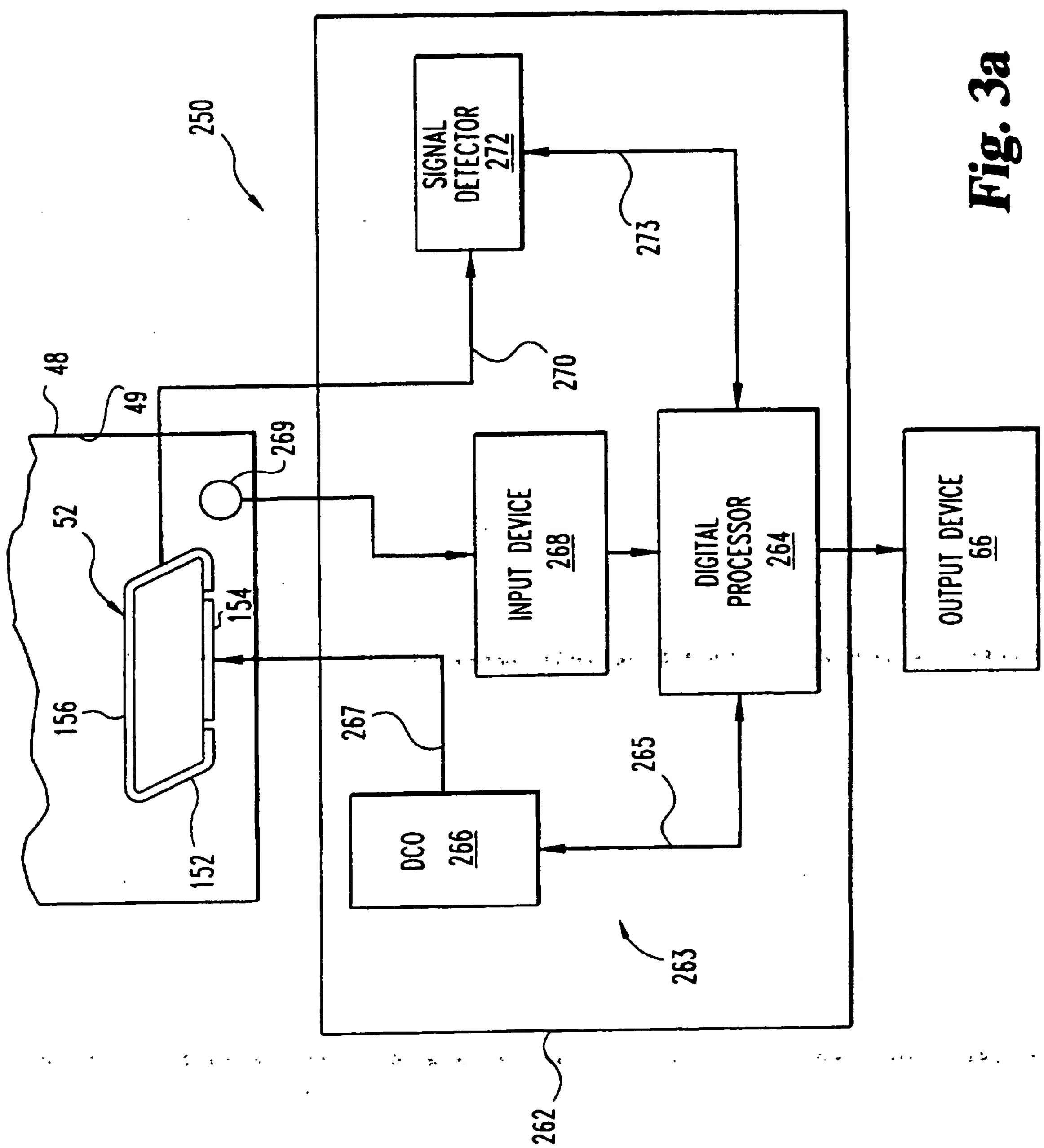
VCO 166
CONTROLLER 164
OUTPUT DEVICE 66
INDICATOR 67
181
62

Fig. 3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DCO 266
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Fig. 3a

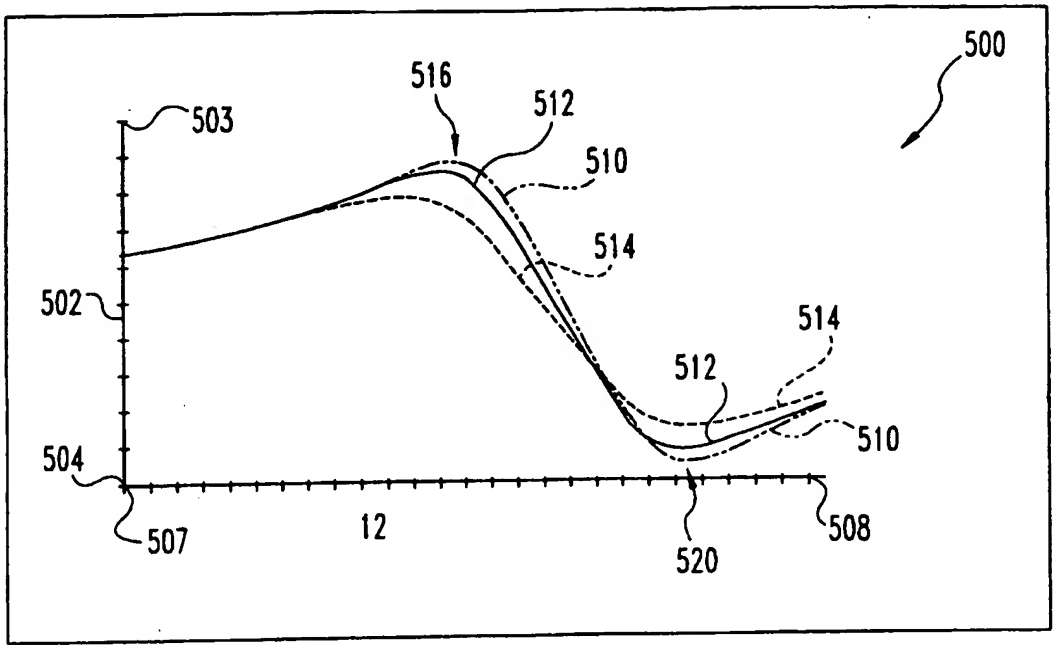
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Fig. 4a

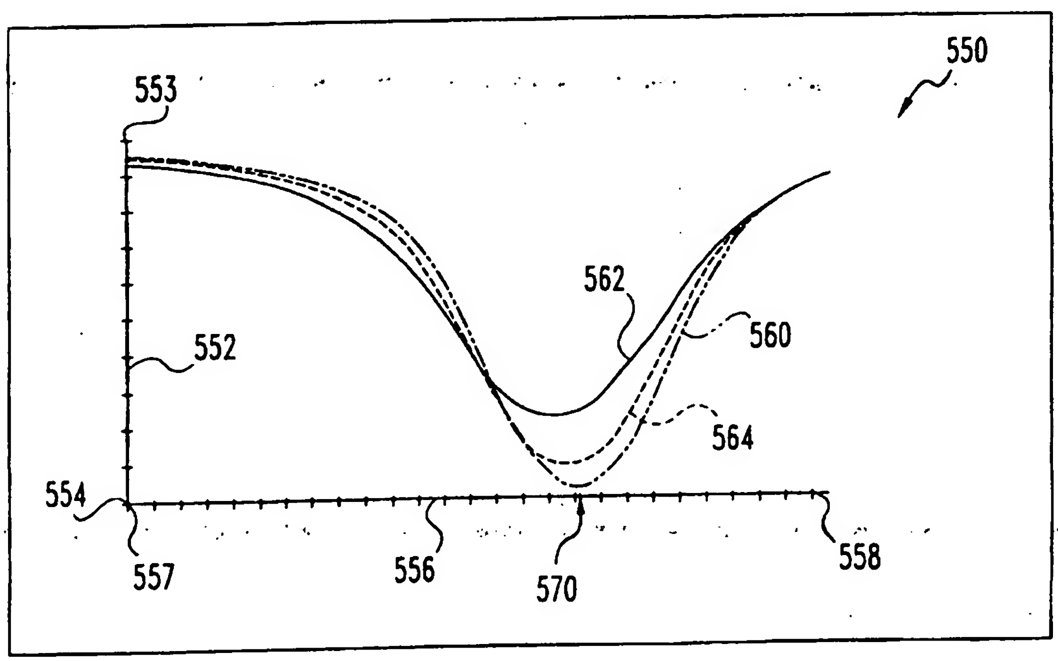
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Fig. 4b

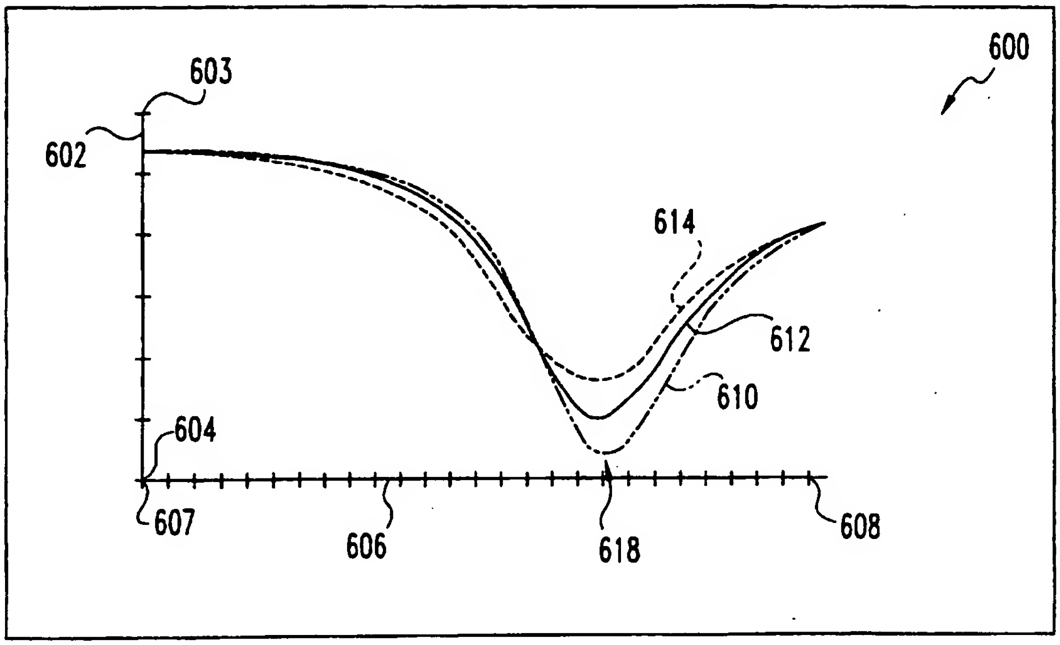
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Fig. 5a

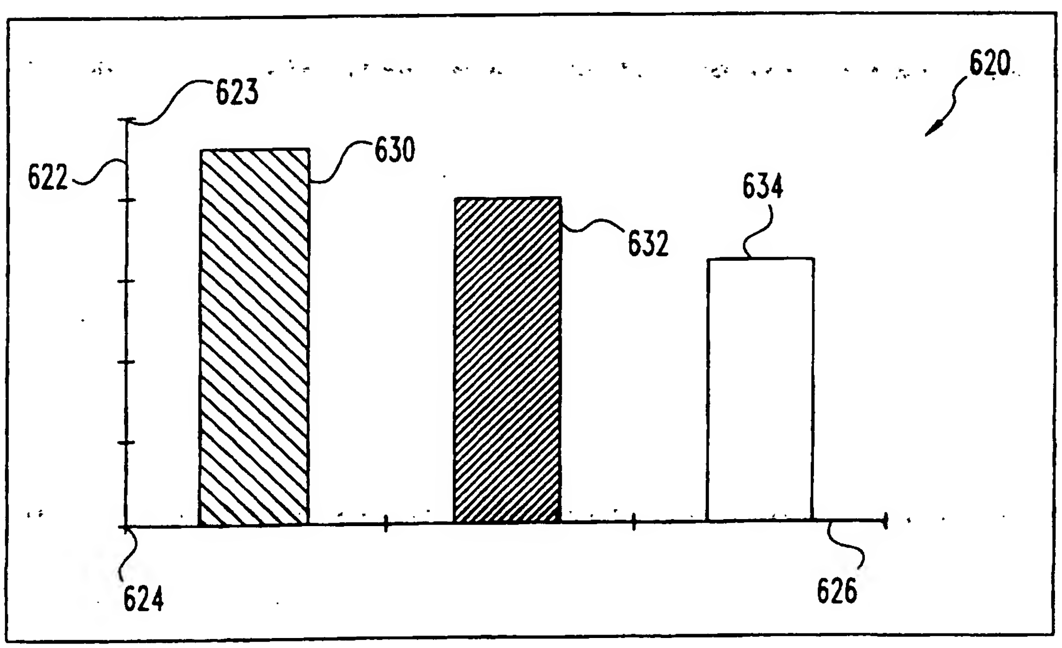
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Fig. 5b

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